Probing dark matter through dark forces

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0903.0363, 0903.3396, 0906.5614

WIMP dark matter

What do(nt) we know in terms of non-gravitational interactions?

- Assuming a thermal relic [following BBN]

  ➔ $\langle \sigma_{ann} v \rangle_{f.o.} \simeq 1\, pbn$

- Upper bounds on other interaction rates

  $\langle \sigma_{scat} v \rangle_{dec}$ ➔ Phase space

  $\langle \sigma_{ann} v \rangle_{gal}$ ➔ Indirect detection

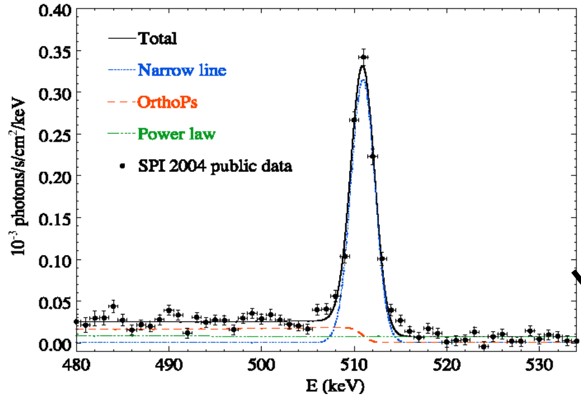
  $\langle \sigma_{scat} v \rangle_{N}$ ➔ Direct detection

- Strongest usually on nuclear elastic scattering

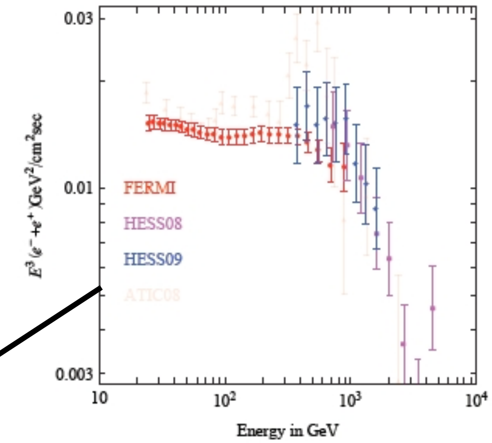
  ➔ $\langle \sigma_{elas} v \rangle_{\mathrm{nuc}} < 1\ \mathrm{pbn}$ (if in sensitivity range)

  ➔ if coherent $\sigma_N < 10^{-7}\ \mathrm{pbn}$

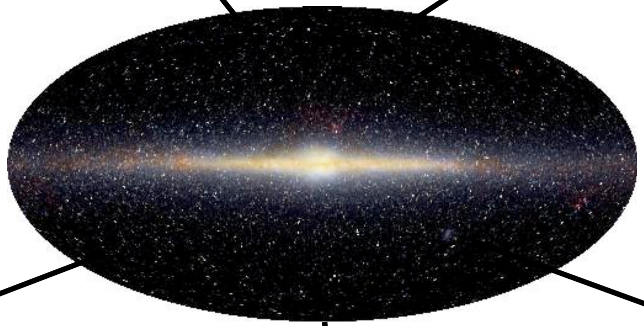
Observational "Hints"

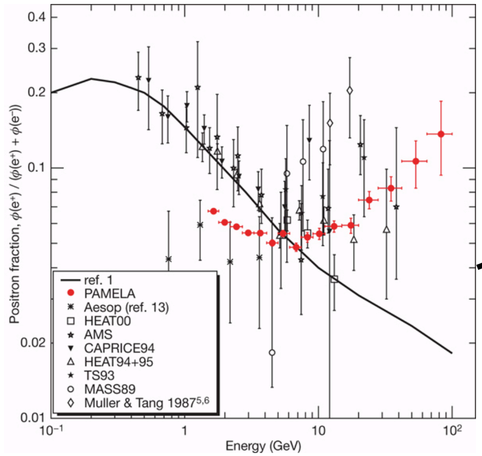


INTEGRAL/SPI

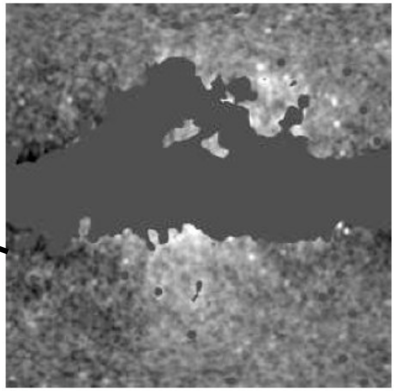


ATIC/FERMI/HESS

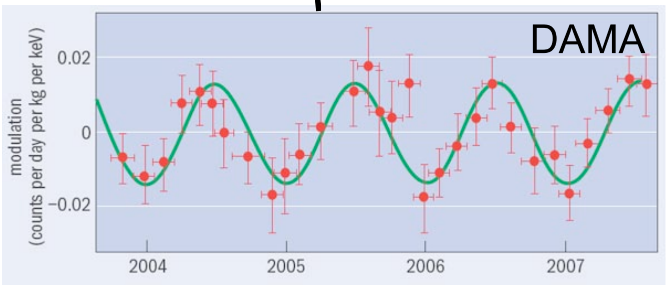




PAMELA



WMAP
haze



Implications?

If any of these effects were to be due to dark matter, we need (some combination of):

- Large galactic annihilation cross-section
- A significant branching to leptons
- More complex nuclear scattering

i.e. a non-standard WIMP candidate

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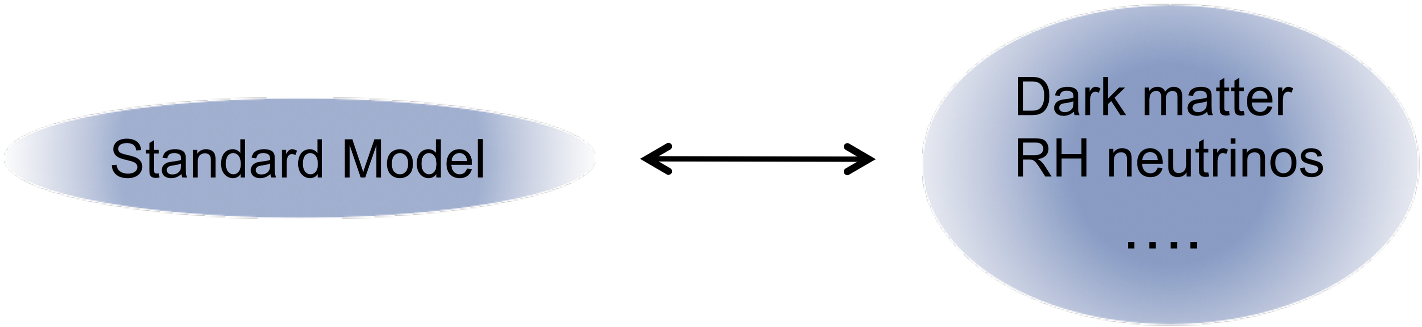
➔ sufficient motivation (for this talk!) to explore dark matter as part of a larger (multi-component, interacting) dark sector

[cf. Arkani-Hamed et al ’08, ...]

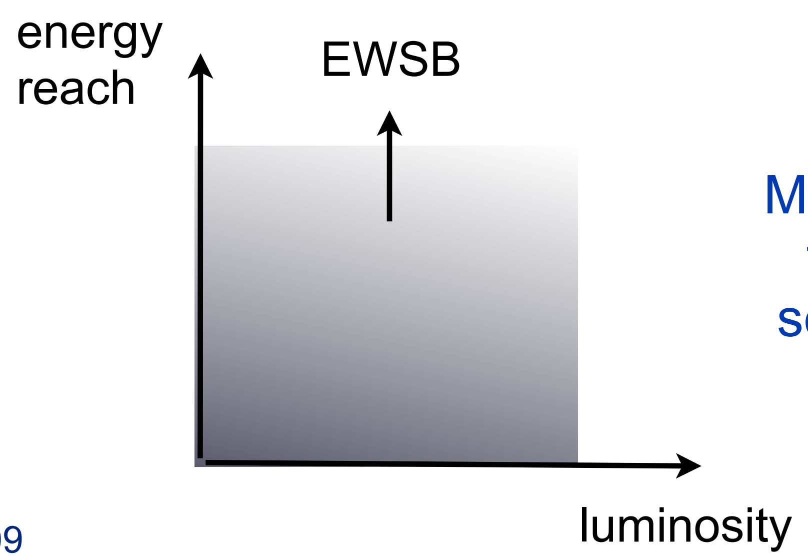
Q: Does this more general framework point to new observational probes?

New physics in a hidden sector

Empirical evidence for new physics does not always point to the EW scale and above, but rather to a hidden sector



Hidden sector may contain "light" states, if neutral under SM gauge group
["hidden valleys" in collider phen, Strassler & Zurek]



Motivates the luminosity frontier as a place to search for new physics

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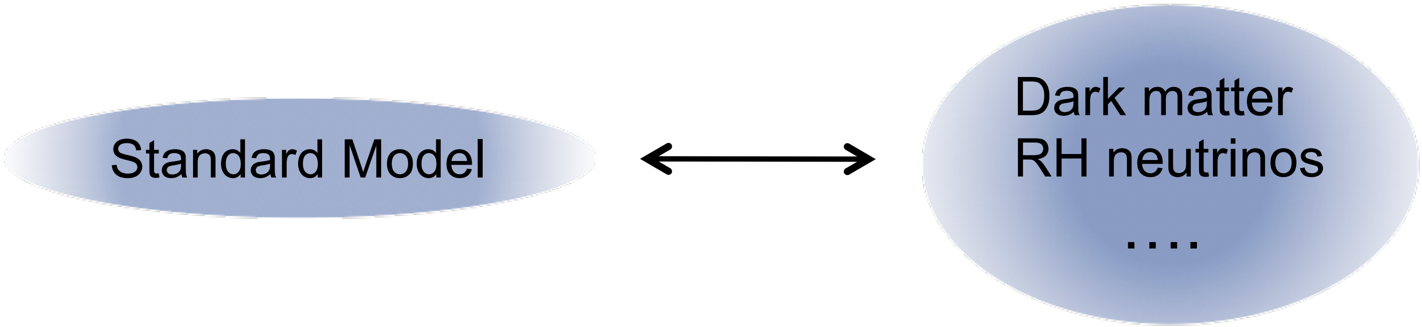

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Allowing dark matter to annihilate into the hidden sector is a simple means of decoupling σ_{ann} and σ_{scat}

- the products of annihilation can mediate very weak interactions with the SM, as they may be long-lived (τ~1s)
- when light, this also allows for possible enhancement/suppression, relevant for existing (astrophys) anomalies: DAMA, PAMELA, etc.

Probing a hidden (dark) sector

Standard Model ⟷ Hidden Sector

$$\mathcal{L}_{med} = \sum_{n,k,l}^{n=k+l-4} \frac{O_k^{(SM)} O_l^{(med)}}{\Lambda^n}$$

Generic interactions are irrelevant (dimension > 4), but there are three renormalizable "portals"

- Vector portal: $\mathcal{L} = -\frac{\kappa}{2} V^{\mu\nu} B_{\mu\nu}$
- Higgs portal: $\mathcal{L} = (-\lambda S^2 + \xi S) H^\dagger H$
- Neutrino portal: $\mathcal{L} = -y_{ij} \bar{L}_i H N_j$

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NB: The vector mediator V can naturally be light ($M \ll M_Z$) implying a new (dark) force

A secluded U(1)

Its straightforward to write down a simple realization of the vector portal

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$ [Holdom '86]

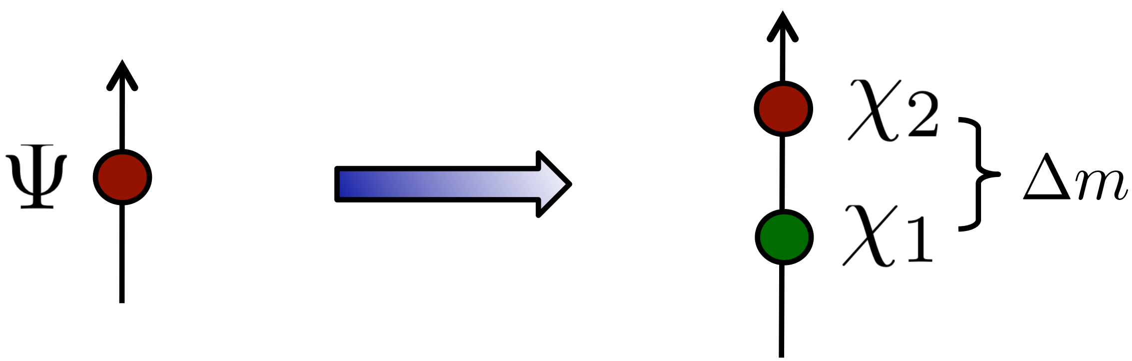
- Weak-scale states charged under $U(1)_S$ are WIMP dark matter candidates [Pospelov, AR, Voloshin '07; Hooper & Zurek '08; Arkani-Hamed et al '08; Pospelov, AR '08; Batell, Pospelov, AR '09]

$$\Rightarrow \quad \alpha' \simeq 10^{-2} \times \left(\frac{m_\chi}{270\,\mathrm{GeV}}\right)$$

- If kinetic mixing arises from integrating out heavy charged states at 1-loop $\Rightarrow \kappa \sim 10^{-3}$, SUSY D-terms then imply $m_V \sim O(\mathrm{GeV})$ [Arkani-Hamed & Weiner '08, Baumgart et al '09; Cheung et al '09; Katz & Sundrum '09]
- We will take the secluded U(1) coupling $\alpha'=\alpha$, so the parameter space = $\{m_V, m_{h'}, \kappa\}$

Multi-component WIMP states

- Enhanced annihilation (e.g. Sommerfeld enhancement) generally requires multi-component (e.g. Dirac) WIMP states.
- However, direct detection limits point to singlets, without any (axial-)vector couplnigs, so consider a generic case...

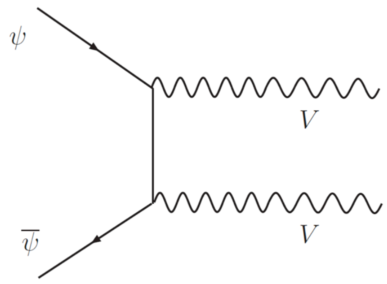


$$\mathcal{L}_{\rm int} = e' V_\mu (\chi_1 \partial_\mu \chi_2 - \chi_2 \partial_\mu \chi_1)$$

This substructure (or a form-factor) also leads to more complex nuclear scattering (cf. DAMA etc).

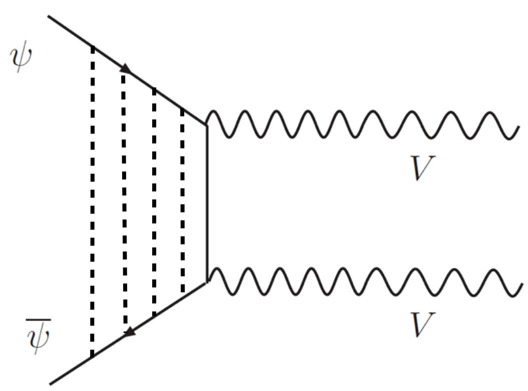
DM Annihilation

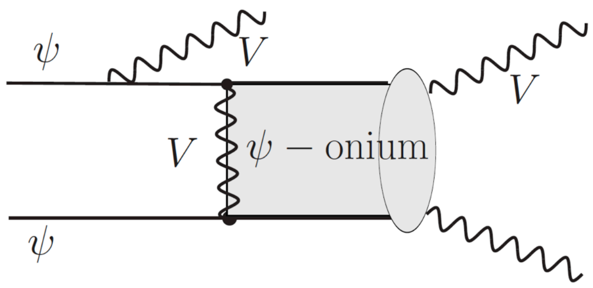
- Relativistic annihilation at freeze-out



Kinetic mixing with γ,Z ⇒
- V decays (mainly) to 2 leptons if m_V < 600 MeV
- V decays (mainly) hadronically if heavier
- Decays to photons are soft, since no 2γ decay

- Non-relativistic annihilation in the galaxy





Enhanced if V is light: $\frac{\langle \sigma v \rangle_{\mathrm{halo}}}{\langle \sigma v \rangle_{\mathrm{f.o.}}} \sim \left\langle \frac{\pi \alpha'}{v} \right\rangle \leq \mathcal{O}\left(\frac{\alpha' m_\chi}{m_V} \right)$

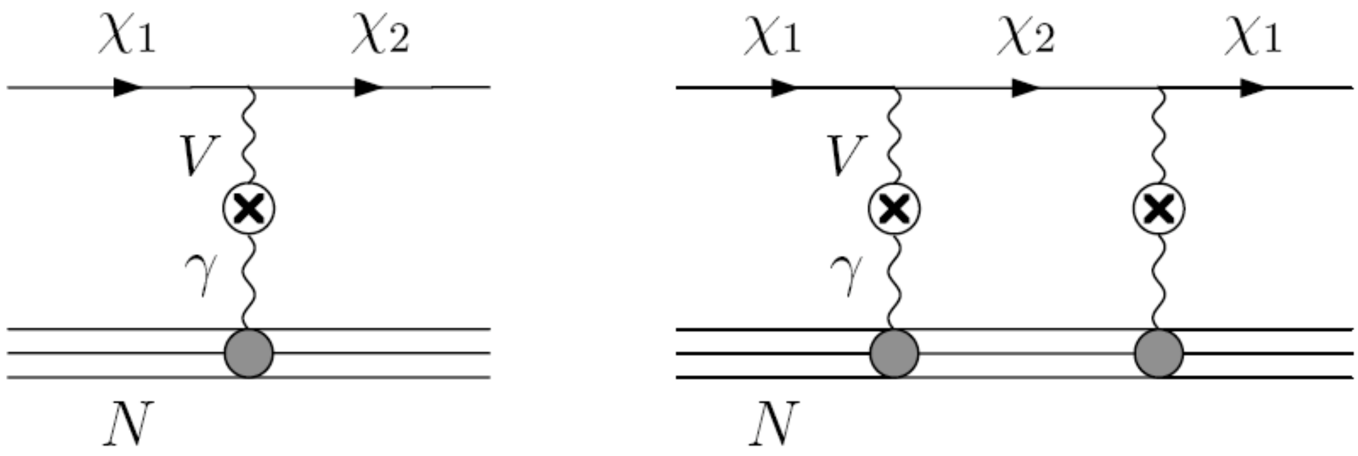
Outline

Given parameters which enhance annihilation in the galaxy, what are the implications for direct detection?

- Implications for nuclear scattering
  - endothermic and exothermic scattering
- Probing dark forces directly
  - fixed targets, neutrino beams & B-factories

1. Direct detection

Nuclear scattering

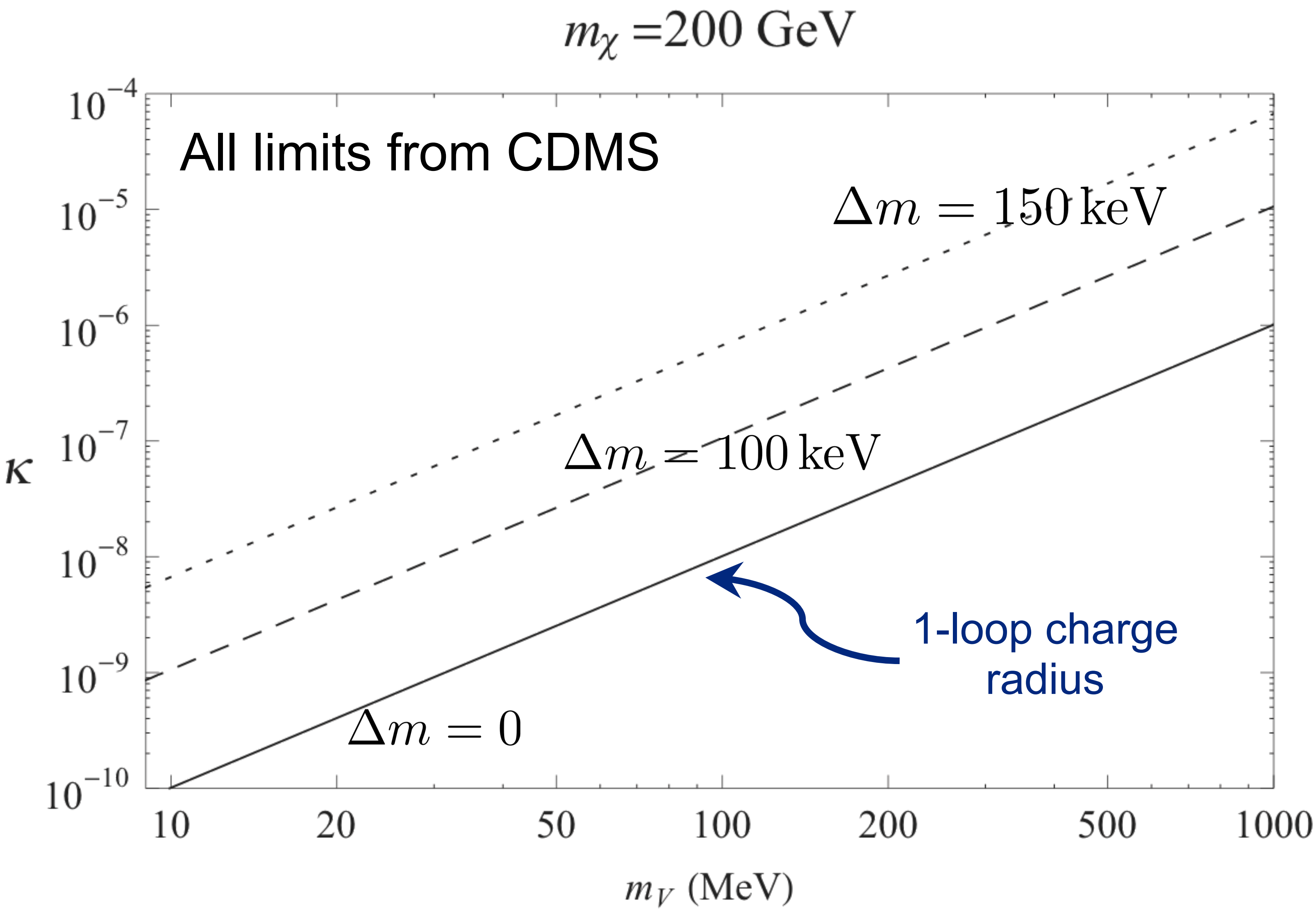


(a)	*elastic scattering* :	$\chi_{(1,2)}N \to \chi_{(1,2)}N.$
(b)	*endothermic scattering* $(Q = -\Delta m)$:	$\chi_1 N \to \chi_2 N.$
(c)	*exothermic scattering* $(Q = \Delta m)$:	$\chi_2 N \to \chi_1 N.$

[as in `inelastic dark matter' Tucker-Smith & Weiner '01]

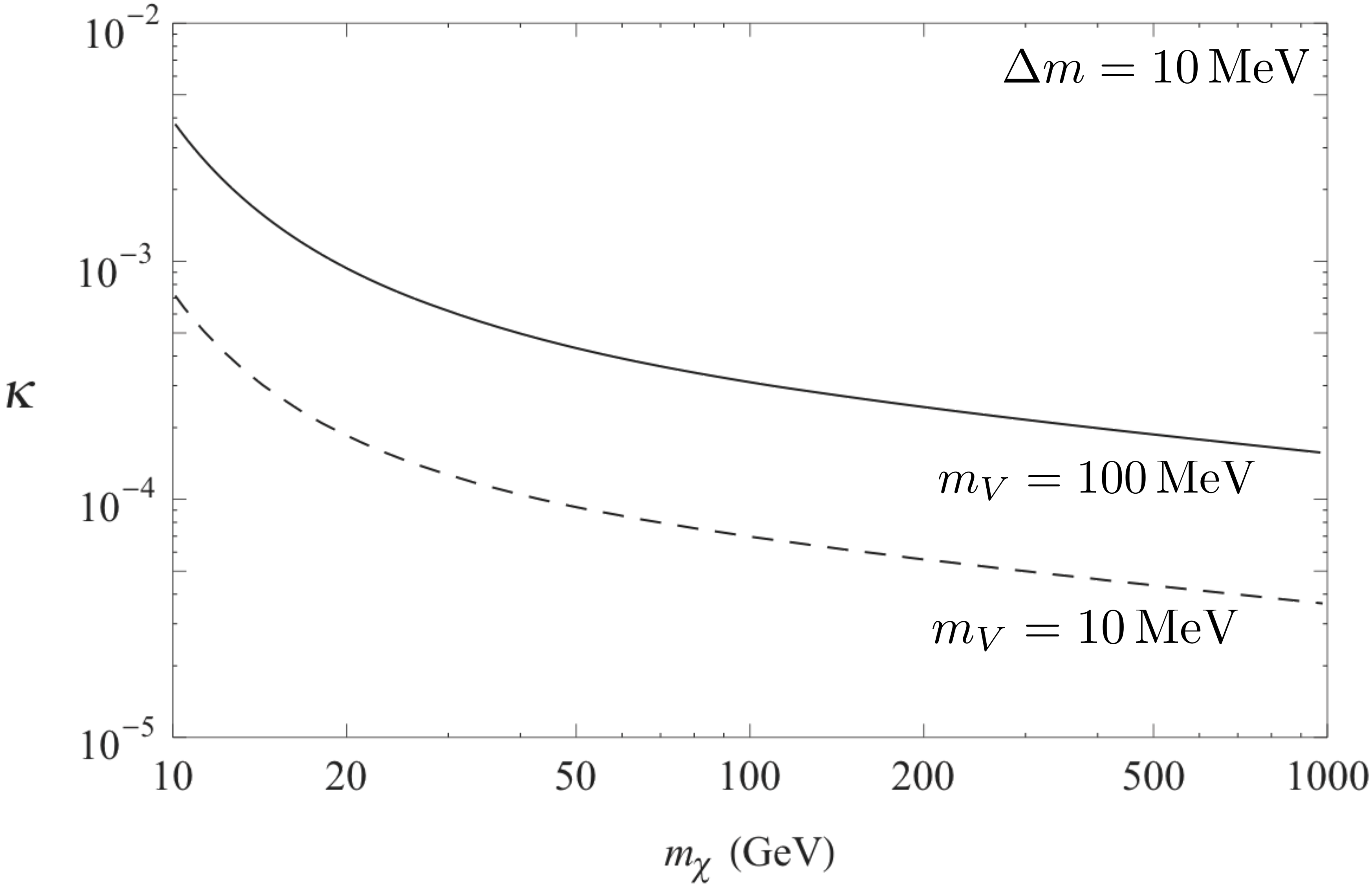
[also: Han & Hempfling '97; Hall, Moroi, Murayama '97]

Endothermic inelastic scattering



scattering not possible for Δm > 190 keV at CDMS

2nd-order Elastic scattering



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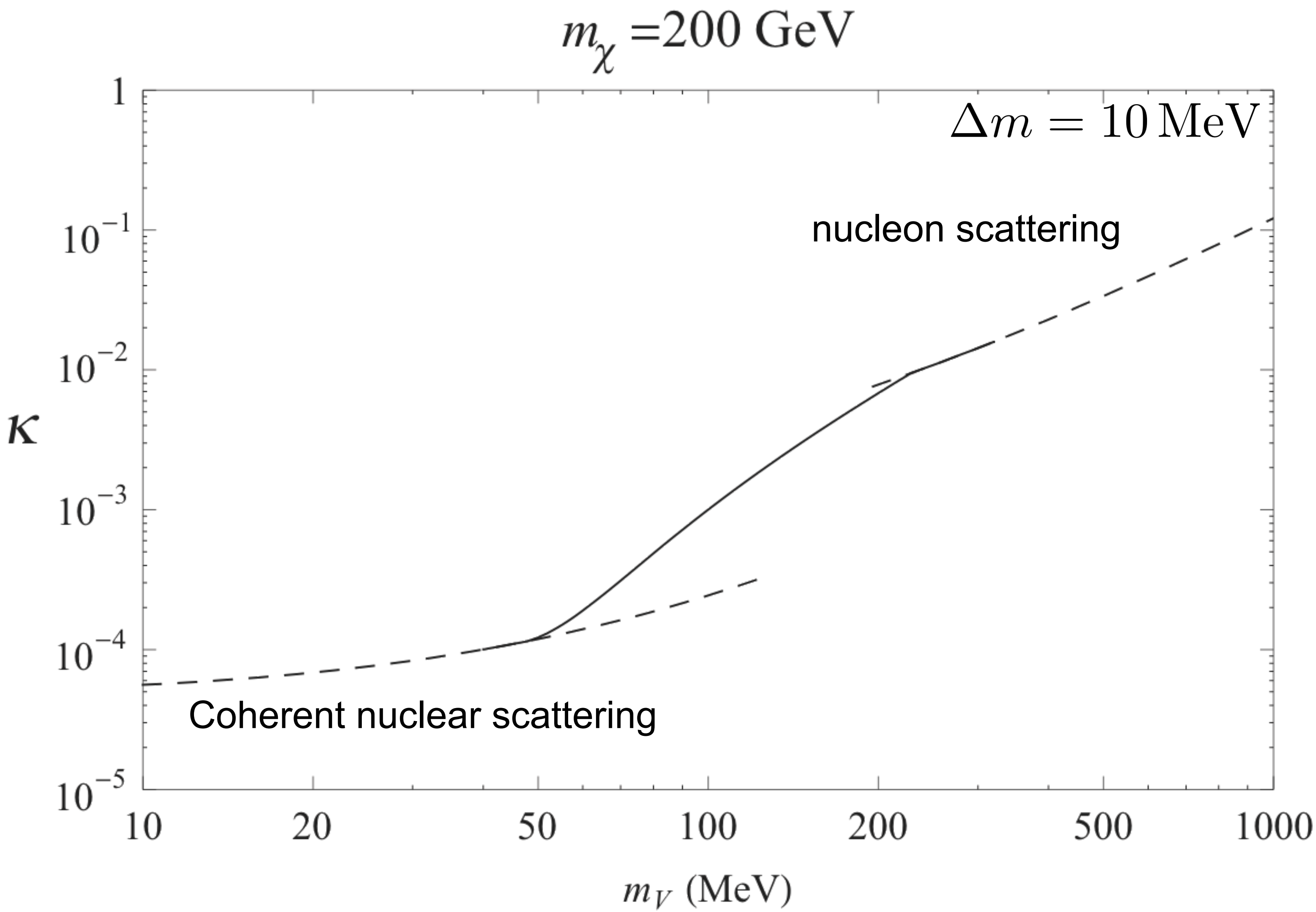


Relic χ_2 & exothermic scattering

- After decoupling and freeze-out of interconversion:

$$\left[\frac{n_2}{n_1}\right]_{\min} \simeq 10^{-2} \times \left(\frac{m_\chi}{300\,\mathrm{GeV}}\right)^{5/2} \left(\frac{10\,\mathrm{MeV}}{T_{\mathrm{D}}}\right)^{1/2}$$

[further upscattering in the galaxy, but generally subdominant, as in XDM Finkbeiner, Weiner '07; Pospelov, AR '07]

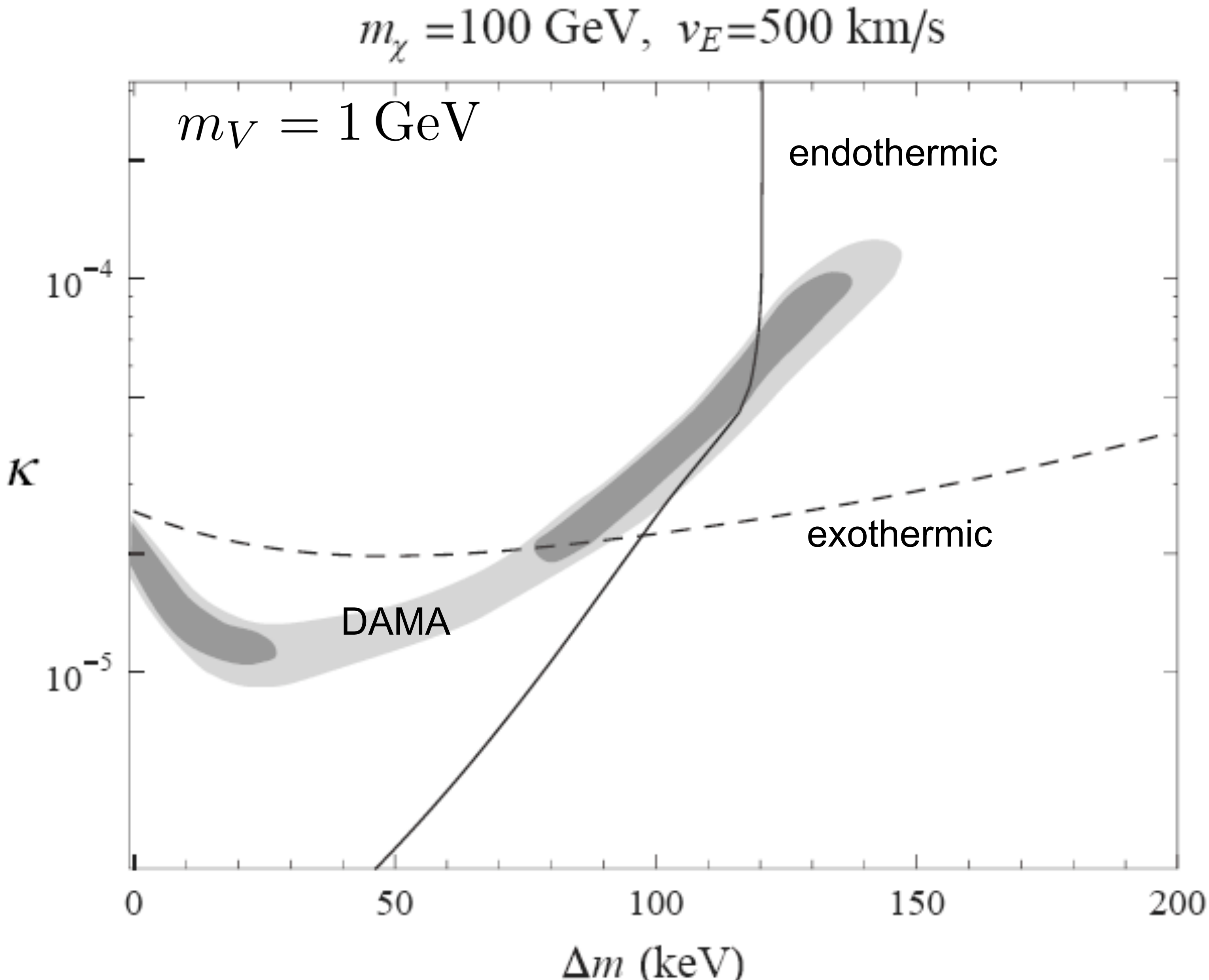
- Decays are highly suppressed (for $\Delta m < 2m_e$):

$$\Gamma_{\chi_2 \to \chi_1 + 3\gamma} \gg \frac{1}{\tau_U}, \qquad \Gamma_{\chi_2 \to \chi_1 \nu\bar{\nu}} \gg \frac{1}{\tau_U}$$

➔ Exothermic down-scattering is a possible direct detection signature!

[see also Finkbeiner, Slatyer, Weiner and Yavin '09]

Exothermic scattering



Summary (part 1)

A multi-component dark matter sector, with near-degeneracies, can significantly modify the signatures for direct detection:

- endothermic and exothermic nuclear scattering is possible
- exothermic scattering of metastable states leads to a rather generic constraint on multi-component WIMP sectors
- significant element-dependence (generic for inelastic DM)

2. Direct probes of dark forces

Probing a secluded U(1) directly

We can also consider experimental probes of the vector portal directly, independent of dark matter

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + |D_\mu\phi|^2 - V(\phi)$$

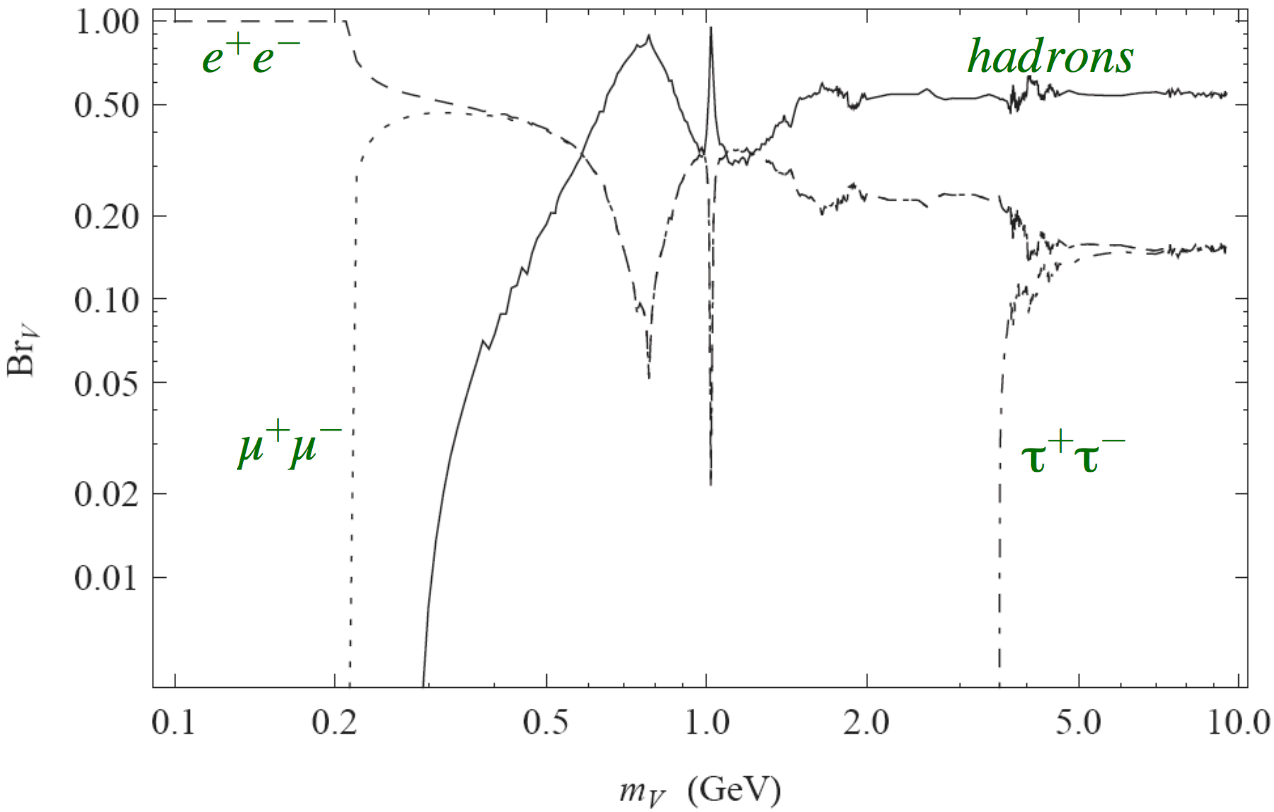
$$\Downarrow$$

$$\mathcal{L}_{int} = -\kappa e V_\mu J^\mu_{em} + \frac{m_V^2}{v'}h' V_\mu V^\mu$$

V - production through mixing with EM current: O(κ^2)

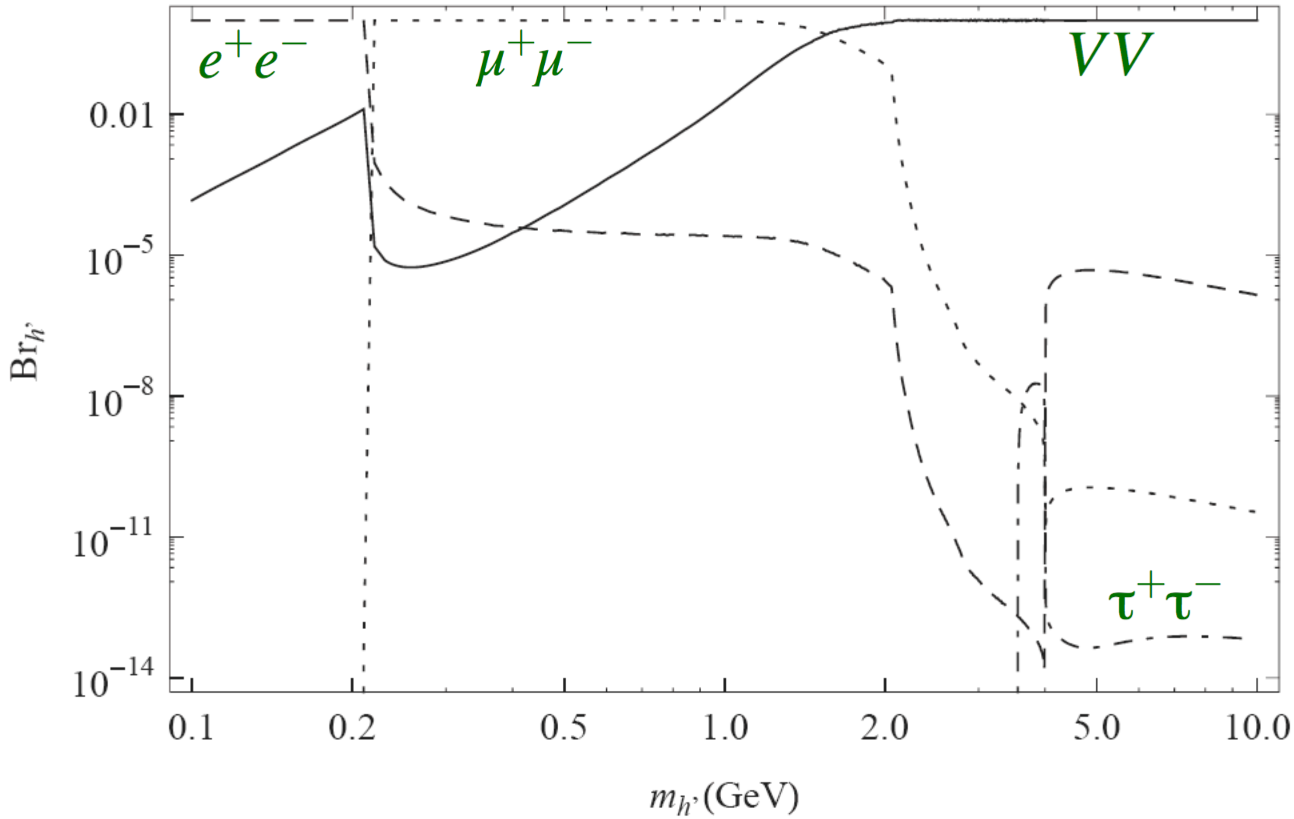
h' - production through higgs'strahlung: O(κ^2)

Vector decays



Parametrically: $\Gamma_V(V \to 2l) \sim O(\kappa^2)$

Higgs' decays



$m_V = 2\,GeV$

When the higgs' is light ($m_{h'} < m_V$), it is parametrically long-lived:

$\Gamma_{h'}(h' \to 2l) \sim O(\kappa^4)$ For κ < 10^{-2}, this can be > 10^6 m

Experimental Sensitivity

Luminosity matters!

- Fixed targets (proton & electron beams dumps)

  - up to 10^{23} POT for modern neutrino sources
  - sensitive to long-lived states

- Medium energy colliders (BaBar, Belle, KLOE,...)

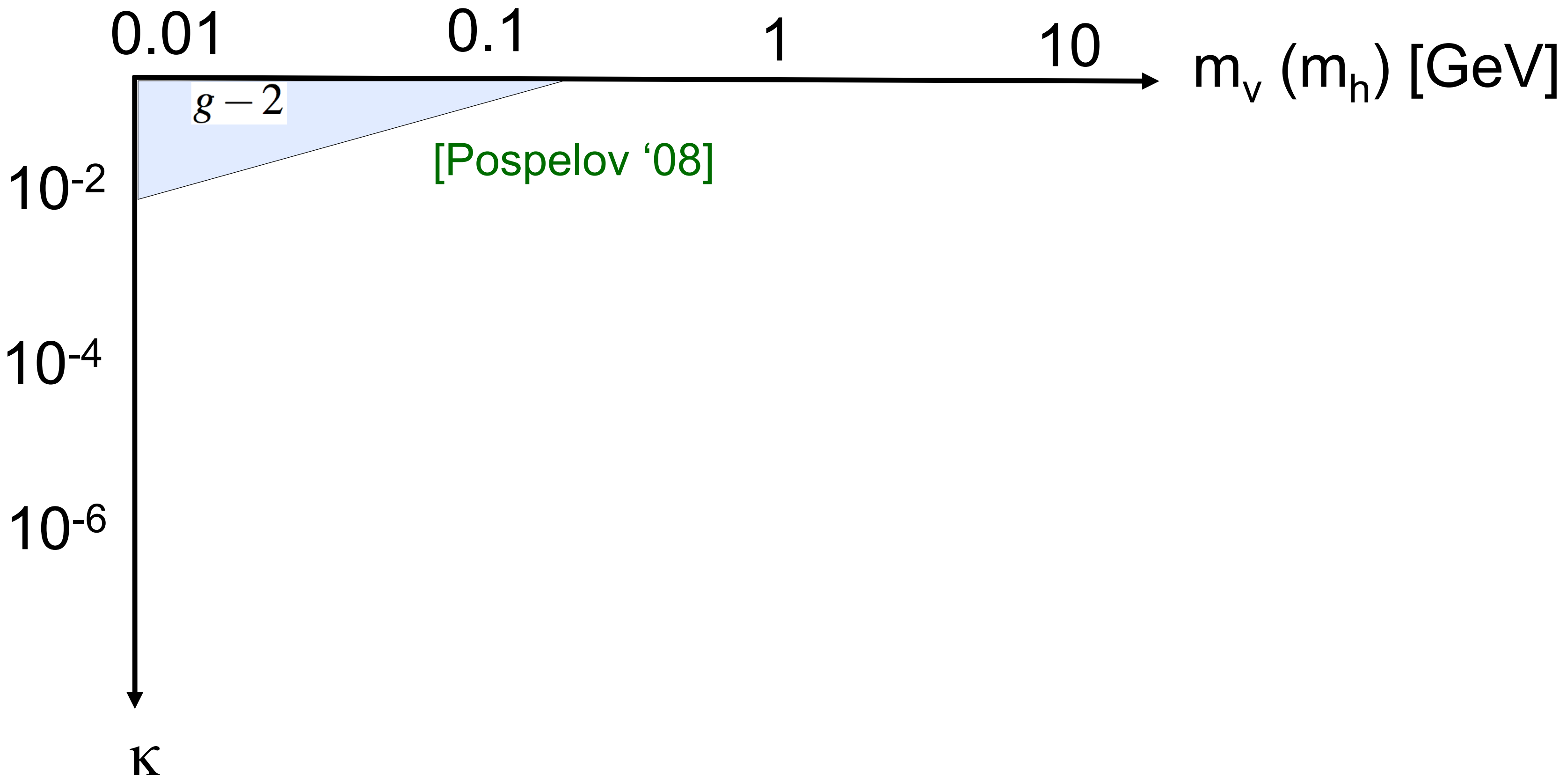
  - large datasets ~ O(1500) fb^{-1}
  - $\sqrt{s}$ ~ 10 GeV

- Rare decays

  - high statistics e.g. for kaon decays

Experimental Sensitivity

In pictorial form



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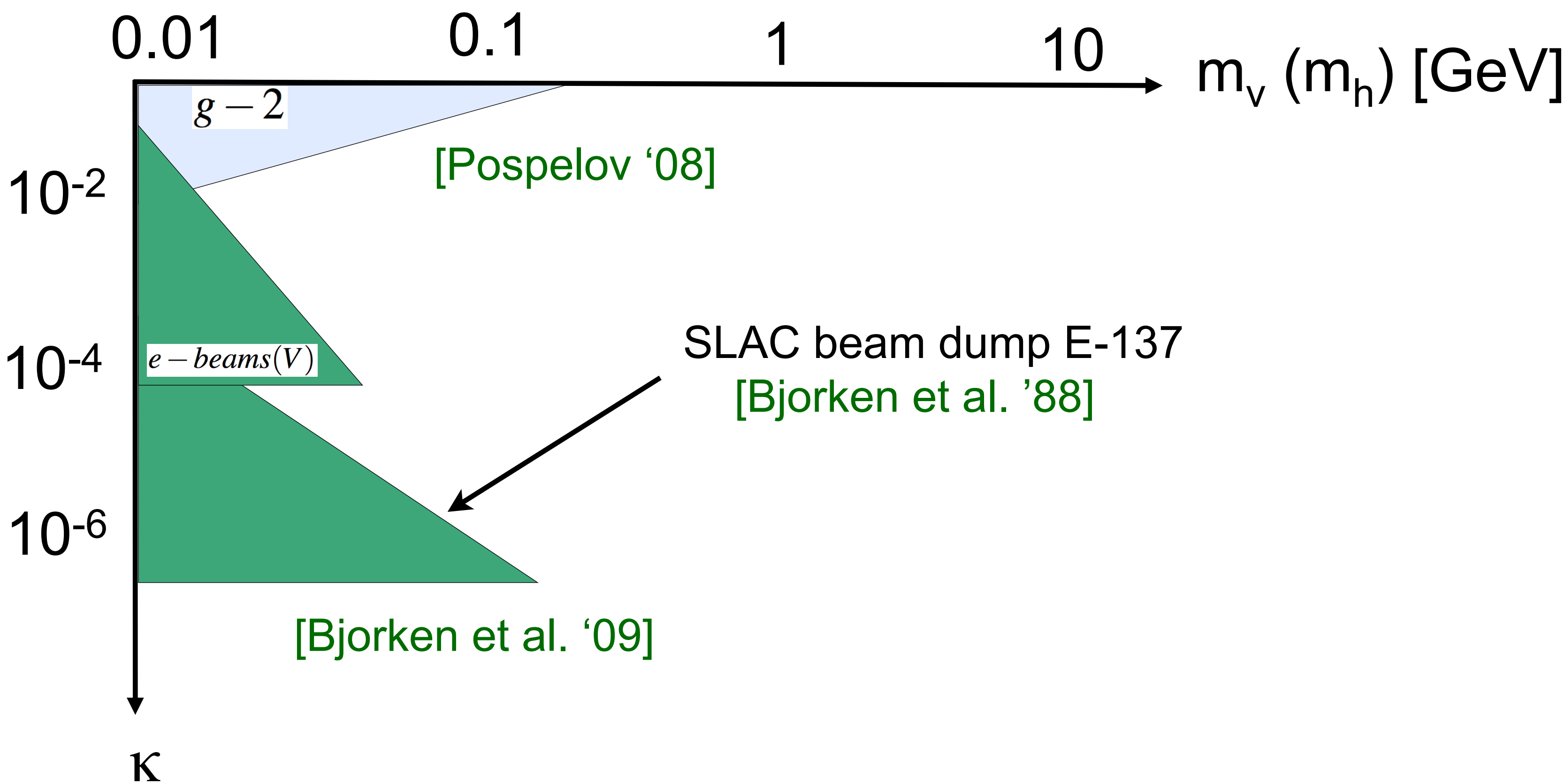
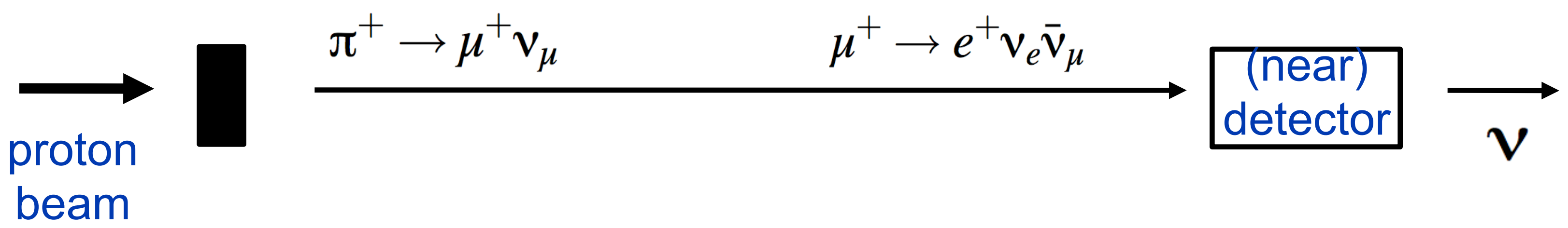
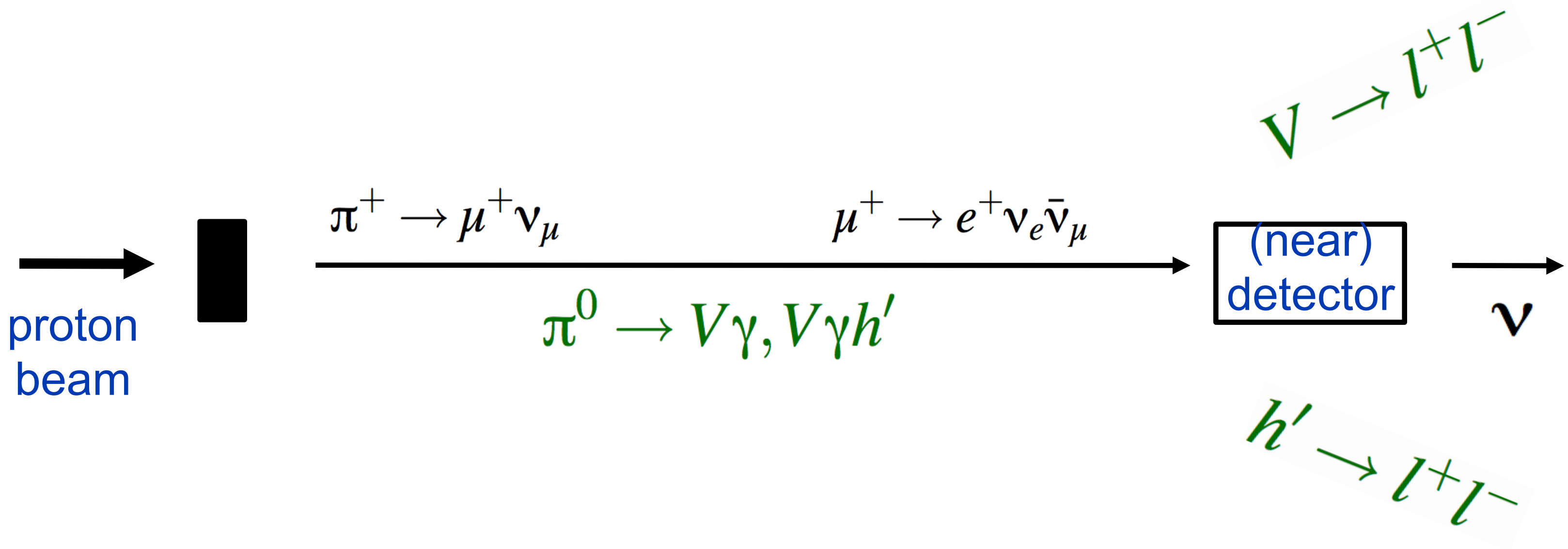


Fixed target probes - Neutrino Beams



Neutrino Beams

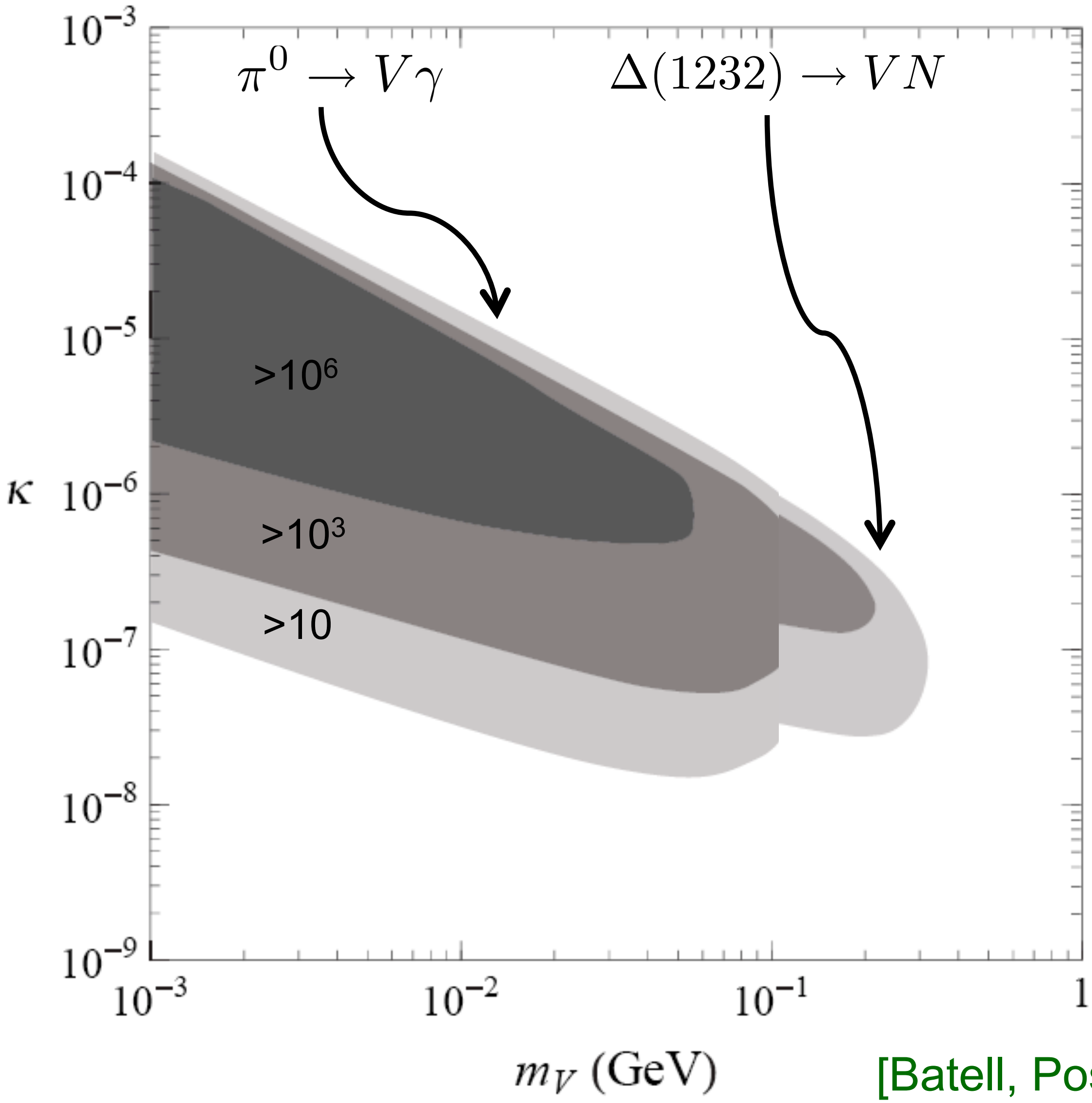


V sensitivity: $\Gamma_V \sim O(100m) \Longrightarrow \kappa \sim 10^{-6} - 10^{-7}$

h' sensitivity: $\Gamma_{h'} \sim O(100m) \Longrightarrow \kappa \sim 10^{-2} - 10^{-3}$

Sensitivity to Vectors

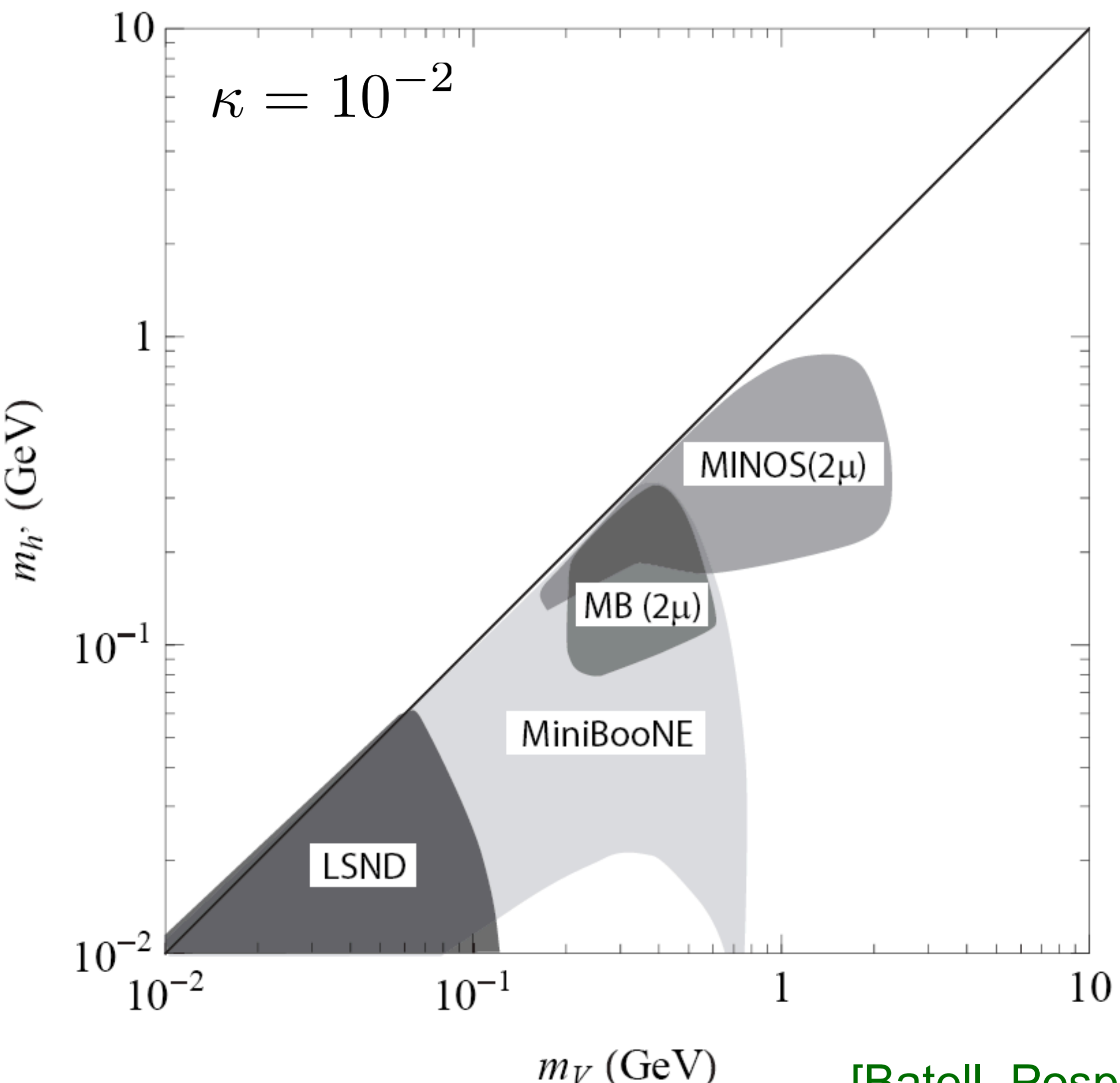
LSND: Distance to detector = 30m, 10^{23} protons on target!



[Batell, Pospelov, AR '09]

Sensitivity to Higgs'

From LSND, MiniBooNE, NuMI/MINOS, …



[Batell, Pospelov, AR '09]

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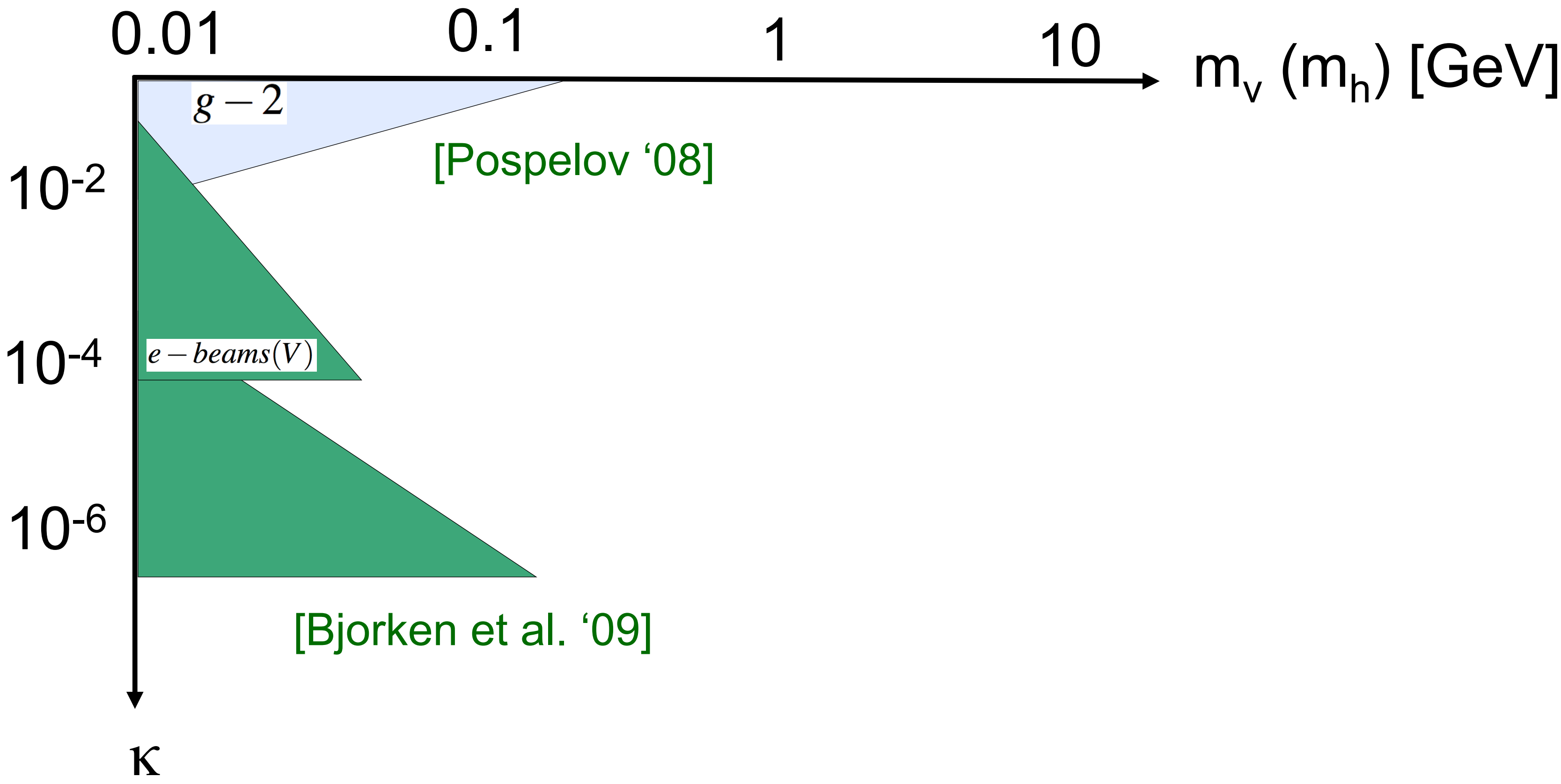
In pictorial form



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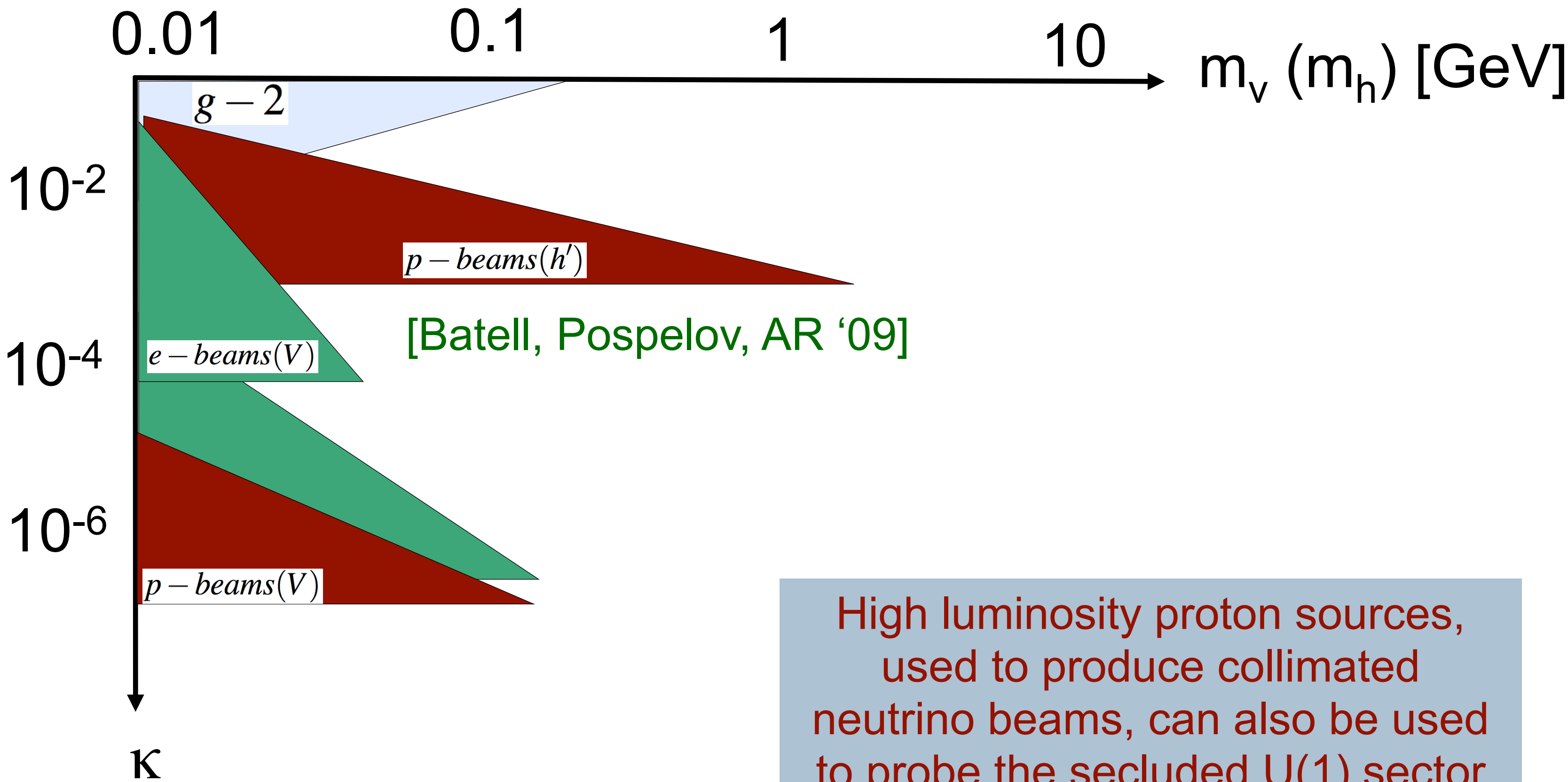
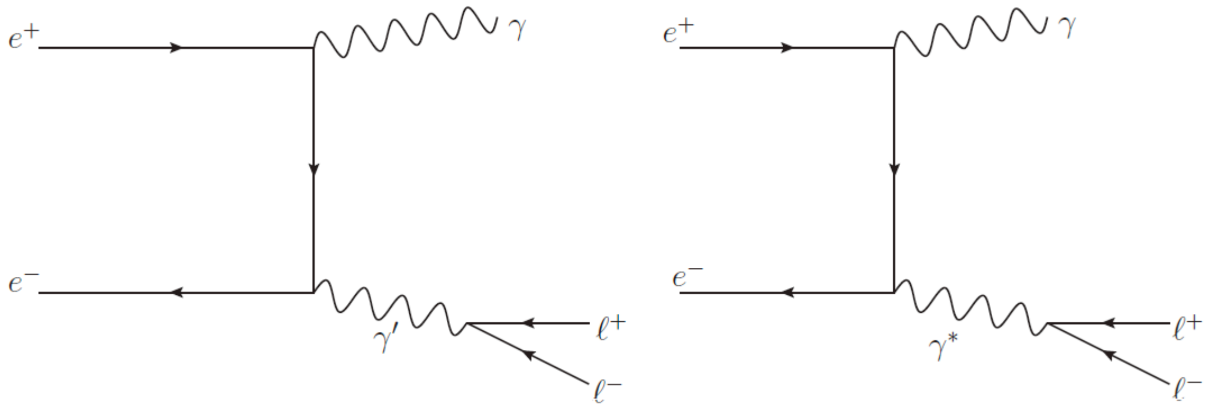


High luminosity proton sources, used to produce collimated neutrino beams, can also be used to probe the secluded U(1) sector

Collider probes - B-factories

Simplest (and perhaps most generic) process is $e^+e^- \rightarrow V\gamma$ with $V \rightarrow$ leptons

[Borodatchenkova et al. '05]
[see also: Essig et al. '09;
Reece & Wang '09]



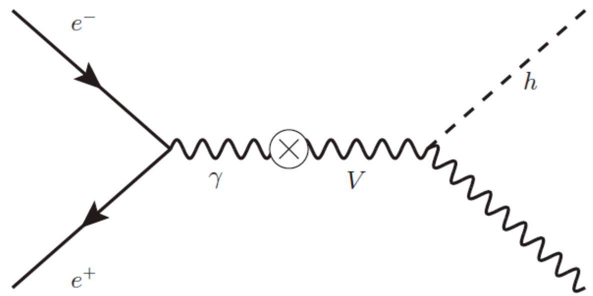
However, there is always a background process with γ^*, which means hunting for a bump in dilepton mass

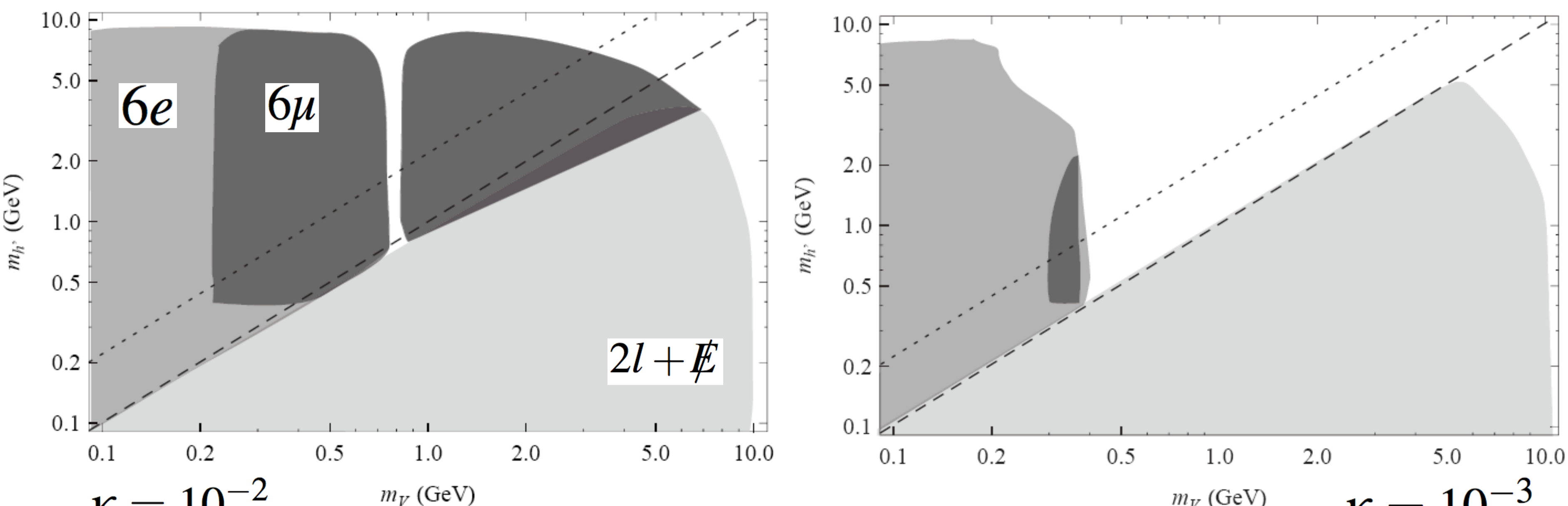
[analyses from BaBar, and future work from Belle, BES-III]

NB: primarily continuum V-production, $\Upsilon(nS)$'s give a small correction

Collider probes - B-factories

Higgs'strahlung: $e^+e^- \longrightarrow Vh' \longrightarrow 6l \;\; (or\; 2l + \not{E})$





$\kappa = 10^{-2}$ $\kappa = 10^{-3}$

[Batell, Pospelov, AR '09]

[see also: Essig et al. '09; Reece & Wang '09]

Experimental Sensitivity

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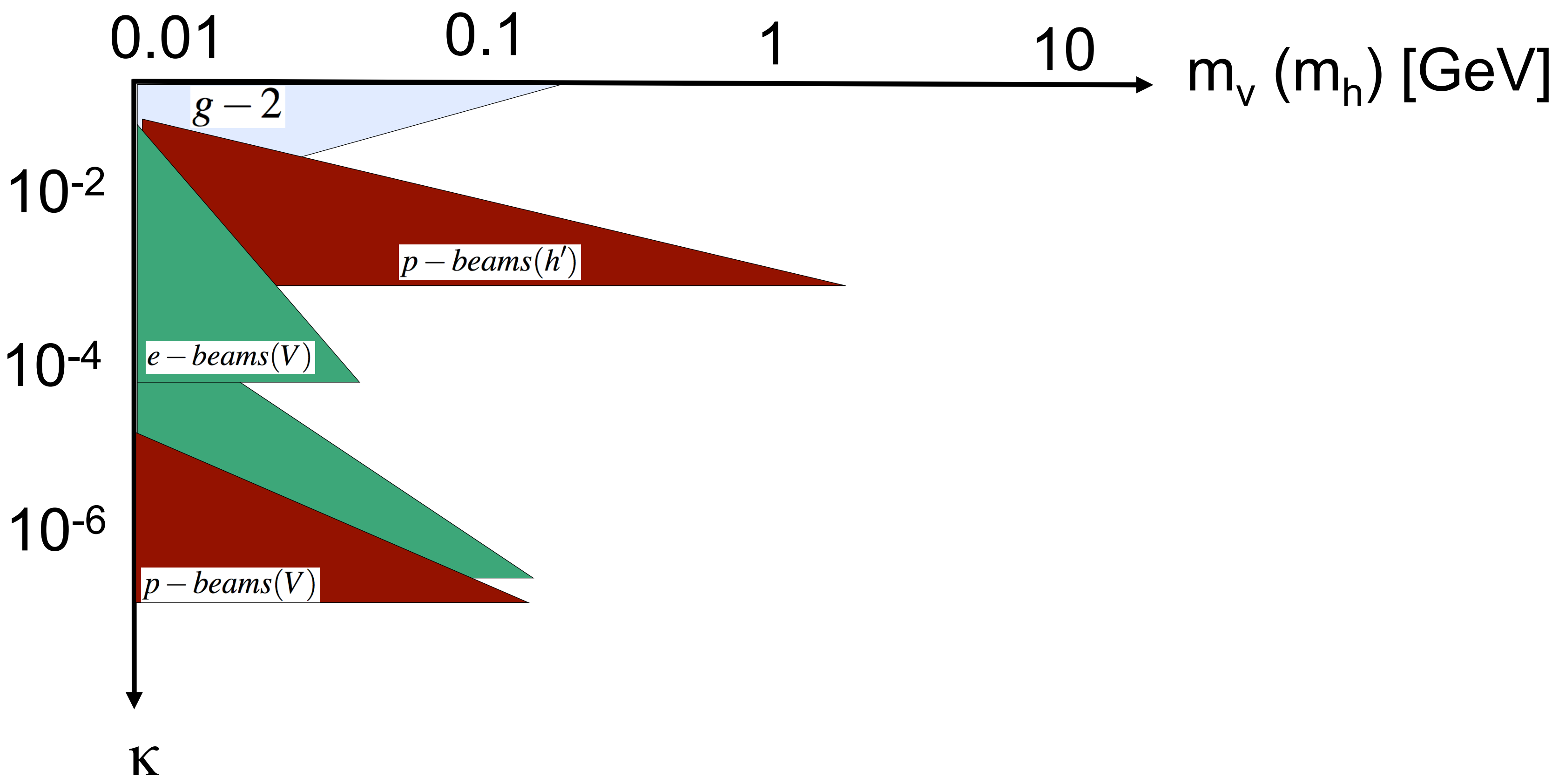

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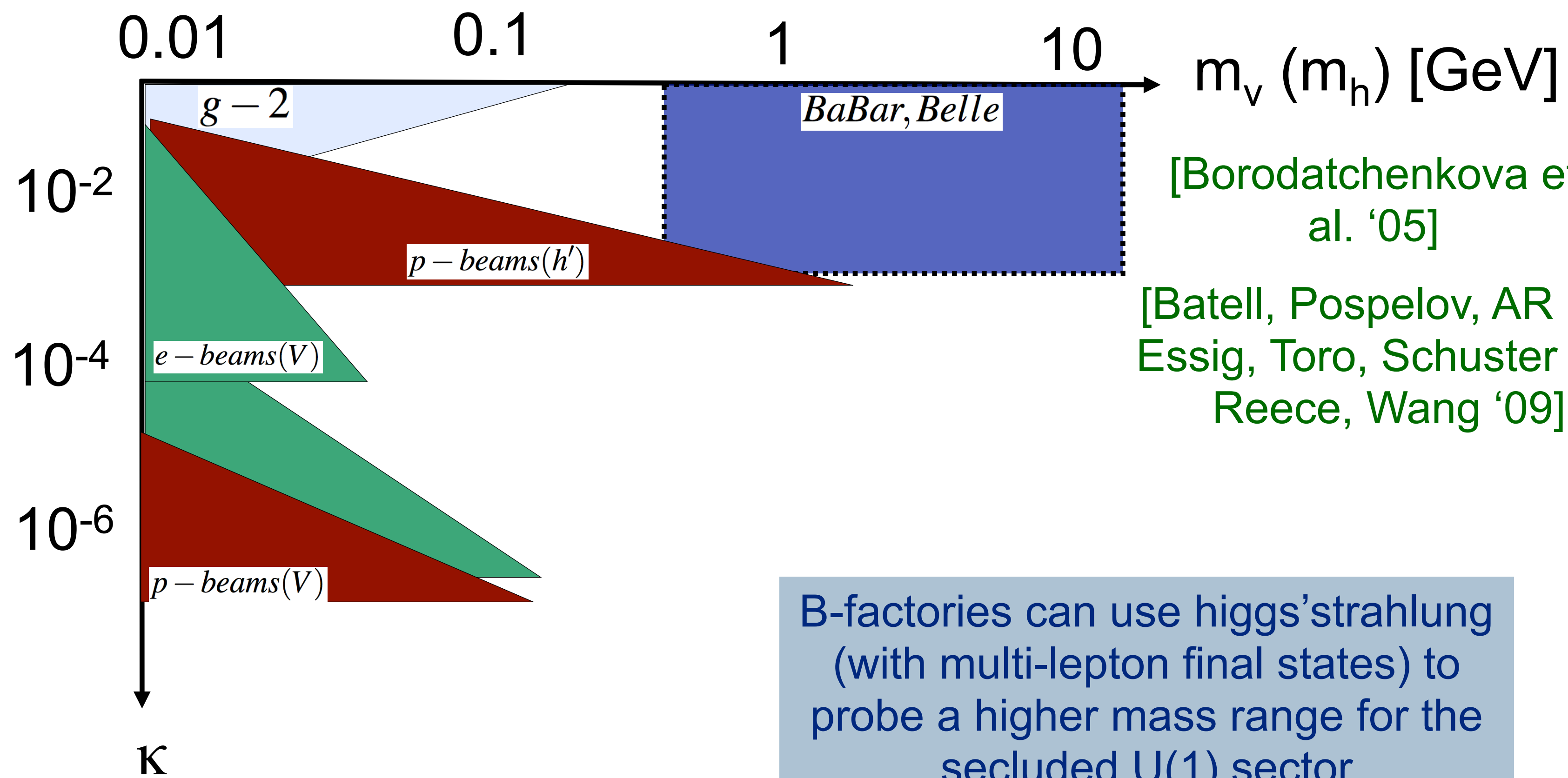

[Borodatchenkova et al. '05]

[Batell, Pospelov, AR '09; Essig, Toro, Schuster '09; Reece, Wang '09]

B-factories can use higgs'strahlung (with multi-lepton final states) to probe a higher mass range for the secluded U(1) sector

Other direct signatures

Subject of recent activity

www-conf.slac.stanford.edu/darkforces2009

- A more complex nonabelian hidden sector allows for other signatures at ee-colliders [Essig et al. '09]

  [Very recent null search at BaBar for $e^+e^- \to W_D W'_D \to 4l$]

- Can also explore rare meson decays (BaBar/Belle, KLOE, KTeV, ...)

$$\mathrm{Br}_{K_L \to \mu^+ \mu^- \gamma} \simeq 3.6 \times 10^{-7}$$

- Interesting signatures (lepton jets) at high energy hadron colliders (SUSY missing energy "comes back" as a lepton jet!) [Arkani-Hamed & Weiner '08, Baumgart et al. '09]

- Proposals for new analyses at B, D, K factories, and new fixed target experiments below hadron threshold

Summary (part 2)

- A neutral hidden sector is an intriguing possibility, motivated by dark matter, RH neutrinos, SUSY breaking, …
- Light degrees of freedom may interact with the SM at the renormalizable level via the vector, Higgs, and neutrino portals
- Sensitivity to these portals lies at the luminosity frontier, e.g. medium energy e^+e^- machines (B-factories), rare decays, fixed targets, …
- Significant sensitivity to a secluded U(1) from neutrino sources: LSND, MiniBooNE, NuMI/MINOS, T2K, NOvA, MicroBooNE, Project X, ...

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